Ultra Intense Laser Pulses: Propagation and Interaction with Plasma

Final Technical Report on DOD-ONR Grant # N00014-93-1-0902

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Technical Monitor: Dr. C. Roberson

Principal Investigator: Prof. R.N. Sudan

Co-Principal Investigator: Prof. B.R. Kusse

This report covers the activities by members of the Laboratory of Plasma Studies, Cornell University under ONR Grant #N00014-93-1-0902 for the period 06/01/93 - 08/31/94.

Personnel

The personnel supported in part by this Grant are listed below:

Principal Investigator

Professor R.N. Sudan

Co-Principal Investigator

Professor B.R. Kusse

Postdoctoral/Research Associate

Dr. X.L. Chen

Dr. K. Krushelnick

Technical Progress Accomplished (6/1/93 - 8/31/94)

The work accomplished is divided into theoretical and experimental parts.

I. Theoretical

(a) The abstracts of papers published in refereed journals under this Grant are given below:

1. "Two-dimensional Self-focusing of Short Intense Laser Pulse in Underdense Plasma", X.L. Chen and R.N. Sudan, *Phys. Fluids B* **5** (4), 1336, April 1993.

Abstract

A simplified set of three-dimensional equations are derived for the propagation of an intense laser pulse of arbitrary

strength $\mathbf{a} = e\mathbf{A}/mc^2$ (where $\mathbf{A}$ is the magnetic vector potential of the laser pulse) in cold underdense plasma. In different limits, the equations can be easily reduced to those of previous one-dimensional models [Phys. Fluids **30**, 526 (1987); Phys. Rev. A **40**, 3230 (1989); **41**, 4463 (1990)]. For $|\mathbf{a}| < 1$, an approximate set of equations from the averaged Lagrangian is obtained. The present study differs from previous work in that wave dispersion is also important for short laser pulse, and is included in the model equations. The axisymmetric two-dimensional model equations are solved numerically to show the effect of dispersion in the self-focusing process.

2. "Necessary and Sufficient Conditions for Self-Focusing of Short Ultraintense Laser Pulse in Underdense Plasma", X.L. Chen and R.N. Sudan, *Phys. Rev. Lett.*, **70** (14), 2082, April 1993.

Abstract

We analyze the propagation of a short intense laser pulse in underdense cold plasma. When no electron cavitation is present, a global invariant H is obtained, and its relation with self-focusing is studied. For relativistic self-focusing, $H < 0$ is a sufficient and necessary condition. For relativistic and ponderomotive self-focusing, $H < 0$ is sufficient but not necessary. Numerical simulations are performed to confirm the above points.

3. "Mechanism for the Generation of 10^9 G Magnetic Fields in the Interaction of Ultraintense Short Laser Pulse with an Overdense Plasma Target", R.N. Sudan, *Phys. Rev. Lett*, **70** (20), 3075, May 1993.

Abstract

The physical mechanism for the generation of very high "dc" magnetic fields in the interaction of ultraintense short laser pulse with an overdense plasma target originates in the spatial gradients and nonstationary character of the ponderomotive force. A set of model equations to determine the evolution of the "dc" fields is derived and it is shown that the "dc" magnetic field is of the same order of magnitude as the high frequency laser magnetic field.

(b) The abstract of the following invited paper presented at the Symposium on Ultra-Intense Lasers at the Annual A.P.S. Meeting, Washington, DC, May 1994 is given below:

1. "Propagation of Intense Laser Pulses in Plasma"*, X.L. Chen†, presented at the APS Meeting, Washington, DC, May 1994.

Abstract

The development of subpicosecond, terrawatt lasers based on the technique of chirped pulse amplification has made extreme nonlinear laser-matter interaction possible at intensities of $\geq 10^{18}$ w/cm^2. Crucial to some of the proposed applications for these lasers is to overcome diffraction and propagate with high intensity over many diffraction lengths. Nonlinear laser-plasma interaction leads to intensity-dependent refractive index which makes the plasma act as an optical guide to compensate for diffraction. A three dimensional code has been developed recently to study the propagation of such a short intense laser pulse ($\geq 10^{18}$ w/cm^2) in underdense plasma, based on previously derived model equations.[1] In the model, we have

assumed a cold plasma and immobile ions. The fully nonlinear simulations of intense laser pulse evolution over many diffraction lengths will be presented. The three dimensional code exceeds the capabilities of usual two dimensional codes, which either assume axi-symmetry or neglect finite pulse duration effect. We are able not only to simulate self-focusing of laser pulse, but also to study the filamentation instabilities which break axi-symmetry and modulation instabilities which break the laser pulse. These three-dimensional simulations will provide hopefully a more complete picture of self-focusing for comparison with experiments.

*Supported by Office of Naval Research and Naval Research Laboratory; Computations performed on the Cornell National Supercomputing Center.

†In collaboration with R.N. Sudan.

[1]X.L. Chen and R.N. Sudan, Phys. Fluids, **B5**, 1336 (1993).

(c) The abstracts of two invited papers published in the Proceedings of the Eleventh International Workshop on Laser Interaction and Related Plasma Phenomena, Oct. 25-29, 1993, Monterey, CA are given below.

1. "Propagation of Intense Laser Pulse in Cold Underdense Plasma"*, X.L. Chen and R. N. Sudan, in *AIP Conference Proceedings 318*, Laser Interaction and Related Plasma Phenomena, 11th International Workshop, Monterey, CA 1993, editor George H. Miley, pp 34.

Abstract

We have derived a simplified set of three dimensional equations for the propagation of an intense laser pulse in cold underdense plasma [Phys. Fluids, **B5**, 1336 (1993)]. A three

dimensional code has recently been developed to study this set of equations. Here we report on some of the preliminary results from the 3-d code.

*This work is supported by Office of Naval Research and Naval Research Laboratory; Computations were performed at the Cornell National Supercomputing Center, supported by NSF and IBM.

2. "Generation of Ultra-High Magnetic Fields by High Power Lasers"*, R.N. Sudan, in *AIP Conference Proceedings 318*, Laser Interaction and Related Plasma Phenomena, 11th International Workshop, Monterey, CA 1993, editor George H. Miley, pp 91.

Abstract

The physical mechanism for the generation of very high "dc" magnetic fields in the interaction of ultraintense short laser pulse with an overdense plasma target originates in the spatial gradients and nonstationary character of the ponder-motive force.

*Work supported by ONR Contract No. N00014-93-1-0902 and NRL Contract No. N00014-90-J-2002.

(d) The abstracts of papers presented at the Annual APS Plasma Physics Meetings are given below.

1. "Propagation and Stability of Intense Laser Pulse in Cold Under-dense Plasma"*, X.L. Chen and R.N. Sudan, presented at the Thirty-Fifth Annual Meeting (Division of Plasma Physics), November 1-5, 1993, St. Louis, MO.

Abstract

We will present the results of a three dimensional code to study the simplified set of equations for the propagation of an intense laser pulse in cold underdense plasma derived previously[1]. In the long pulse limit, we have also obtained necessary and sufficient conditions for self-focusing[2]. The linearized equations in this limit can be written in a variational formulation. Thus an energy principle method is employed to analyse the stability of the laser pulse to filamentation and modulation modes. These results will be compared to simulations.

*Work supported by U.S. Naval Research Laboratory.

[1]X.L. Chen and R.N. Sudan, Phys. Fluids, **B5**, 1336 (1993).

[2]X.L. Chen and R.N. Sudan, Phys. Rev. Lett., **70**, 2082 (1992).

2. "3D Numerical Simulation of Ultra-Intense Laser Pulse in Plasma Channel for Electron Acceleration"*, X.L. Chen and R.N. Sudan, presented at the Thirty Sixth Annual Meeting (Division of Plasma Physics), November 7-11, 1994, Minneapolis, MN.

Abstract

When an ultra-intense laser pulse propagates in an underdense plasma, the ponderomotive force of the laser pulse expels electrons and creates a depression in the electron density with the longitudinal electric field exceeding many Gev/m. The strong electric field has been suggested as a motivation for compact high energy accelerators[1]. A numerical code in three dimensions has been developed[2] to study the model equations

that we have derived earlier[3]. To avoid filamentation and modulation which have been observed in our simulations, we propagate the laser pulse in an externally produced plasma channel. Test electrons are employed to demonstrate: (1) acceleration in the longitudinal electric field, and the quality of this acceleration by computing the evolution of beam emittance; (2) the dependence of such acceleration on the quality of the externally produced plasma channel.

*Work supported by the Office of Naval Research and Naval Research Laboratory. Computations performed at the Cornell Supercomputing Center.

[1] T. Tajima and J.M. Dawson, Phys. Rev. Lett., **43**, 267 (1979).

[2] Chen and Sudan, Bull. Am. Phys. Soc., **39**, 1176 (1994).

[3] X.L. Chen and R.N. Sudan, Phys. Fluids, **B5**, 1336 (1993).

II. Experimental

The experimental activities can be separated into two efforts; 1. The fabrication of a laser system at Cornell and 2. Collaboration with the Naval Research Laboratory on experiments using their ultra high power laser.

(a). The fabrication of the first of three stages of an ultra high power-short pulse laser system at Cornell was completed during this contract period. This first stage has been operational for several months and consists of a mode locked, Ti:sapphire oscillator which puts out a train of pulses at 100 MHz. Each pulse is approximately 100 fsec long at an energy of 2 nJ and a wavelength of 800 nm. The second stage will be a regenerative amplifier followed by a third stage of high power amplification. The last two stages will operate using chirped pulse techniques and we hope to begin fabrication of them soon. In

addition to the completion of this first stage a laser laboratory has been established with plenty of space to accommodate the full laser system and experimental targets. We have begun to put together a set of laser diagnostics and now have operational a Princeton Instruments CCD camera for laser channeling observations.

(b). Since our total laser system at Cornell has not been completed we have sought collaboration with the Naval Electronics Laboratory in order to use their ultra intense-short pulse laser. This laser operates at 1000 nm and can produce focused pulses at an intensity of 10^{18} to 10^{19} Watts/cm^2. The initial experiments on this device have been done in conjunction with NRL personnel and have looked at interactions of the focused laser pulses with plasma targets that include a medium intensity, relativistic, electron beam and an initially neutral plasma jet. The results of these experiments have been prepared for publication and are described in the abstracts that follow.

1. "Intense Laser Interaction Research at NRL—Experiment"*, A. Ting, A. Fisher, R. Fischer, R. Burris[1], K. Evans[2], K. Krushelnick[3], J. Grun, J. Krall, E. Esarey and P. Sprangle, *Plasma Physics Division, Naval Research Laboratory*, presented at the Thirty Sixth Annual Meeting (Division of Plasma Physics), November 7-11, 1994, Minneapolis, MN.

Abstract

The interaction of intense laser pulses with plasmas, electron beams, and materials is being investigated at the NRL T^3 laser facility. The facility provides both ps, TW, and ns, kJ laser pulses. The experiments include: 1) x-ray generation by Thomson scattering of an intense laser pulse from a relativistic electron beam (Laser Synchrotron Source), 2) harmonic generation in an underdense plasma by backscattering of an intense laser pulse, 3) electron acceleration by laser generated plasma wakefields (Laser Wakefield Accelerator), and others. Discus-

sion of these experimental efforts will be presented.

*Work supported by ONR and DOE.

[1] RSI, Alexandria, VA.

[2] George Mason University, Fairfax, VA.

[3] Cornell University, Ithaca, NY.

2. "Generation of the Second Harmonic of Stimulated Raman Backscattered Light in Underdense Plasmas", K.M. Krushelnick*, A. Ting, H.R. Burris†, A. Fisher and C. Manka, *Plasma Physics Division, Naval Research Laboratory,* submitted for publication in Physical Review Letters.

Abstract

Experiments examining nonlinear scattering mechanisms of high intensity laser light with underdense plasmas were performed using a table top terawatt laser system. At a 45 degree angle from the directly backscattered direction red-shifted second harmonic emission was observed from multiphoton ionized plasmas having electron densities ranging up to 10^{19} cm^{-3}. This result was indicative of electron cavitation due to the laser ponderomotive potential. The frequency of this radiation was found to vary with plasma electron density and the amount of spectral broadening varied with laser intensity.

*Laboratory of Plasma Studies, Cornell University, Ithaca, NY.

† Research Support Instruments, Alexandria, VA.

3. "Extreme Broadening of Stimulated Raman Backscattered Light from High Intensity Laser Plasma Interactions", A. Ting, K.M. Krushelnick*, H.R. Burris†, A. Fisher and C. Manka, *Plasma Physics Division, Naval Research Laboratory, Washington, D.C. 20375*, submitted for publication in Physical Review Letters.

Abstract

High intensity laser-plasma interaction experiments using a table top terawatt laser system were performed to examine nonlinear scattering mechanisms in field ionized underdense plasmas. A very broad Raman backscattered spectrum was observed - extending from 450 nm to > 1200 nm at an incident laser intensity of 2×10^{18} W/cm^2. Large amplitude modulations having a period which varied with frequency were observed in the spectrum. Narrow backscattered features which are attributed to scattering from ion waves were also measured.

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† Research Support Instruments, Alexandria, VA.